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Biomass torrefaction technology: Techno-economic status and future prospects

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ABSTRACT

Torrefaction is a promising bioenergy pre-treatment technology, with potential to make a major contribution to the commodification of biomass. However, there is limited scientific knowledge on the techno-economic performance of torrefaction. This study therefore improves available knowledge on torrefaction by providing detailed insights into state of the art prospects of the commercial utilisation of torrefaction technology over time. Focussing on and based on the current status of the compact moving bed reactor, we identify process performance characteristics such as thermal efficiency and mass yield and discuss their determining factors through analysis of mass and energy balances. This study has shown that woody biomass can be torrefied with a thermal and mass efficiency of 94% and 48% respectively (on a dry ash free basis). For straw, the corresponding theoretical energetic efficiency is 96% and mass efficiency is 65%. In the long term, the technical performance of torrefaction processes is expected to improve and energy efficiencies are expected to be at least 97% as optimal torgas use and efficient heat transfer are realised. Short term production costs for woody biomass TOPs (torrefied pellets) are estimated to be between 3.3 and 4.8 US$/GJ$_{LHV}$, falling to 2.1–5.1 US$/GJ$_{LHV}$ in the long term. At such cost levels, torrefied pellets would become competitive with traditional pellets. For full commercialisation, torrefaction reactors still require to be optimised. Of importance to torrefaction system performance is the achievement of consistent and homogeneous, fully hydrophobic and stable product, capable of utilising different feedstocks, at desired end-use energy densities.

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1. Introduction

Torrefaction is the thermal upgrading of biomass into a more homogeneous product and when densified through pelletisation results in a more energy-dense product – the so-called TOPs (torrefied pellets), which has properties similar to coal. Table 1 compares some key characteristics of coal and various biomass types and shows the improved qualities of TOPs compared to other biomass types. Torrefied biomass has therefore many potential applications – where coal is currently being used – such as a fuel in the heating sector, power generation (cofiring), gasification and steel production (as reducing agents) [1–4]. As a biomass pretreatment technology, torrefaction is still under development and several organizations are currently conducting research, demonstration and pilot schemes [5,6] to improve its operational performance and to achieve commercial competitiveness. Previous research has shown that torrefaction improves the physical characteristics of biomass [7–10], reduces the energy requirement for fine grinding of biomass [11–13,3], improves the co-gasification process of biomass [14,9,15,16,4,17] and has potential to improve the performance of biomass energy supply chains [18–24]. It should be noted that although torrefaction became increasingly popular in recent years, the upgrading and refining of lignocellulosic biomass under prepyrolytic conditions has been investigated earlier when the term prepyrolysis was used. Thermal densification was achieved by combining heating with (mechanical) compression [25,26].

However, scientific knowledge on the performance of different torrefaction technologies is limited and publicly available

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Table 1
Characteristics of selected biomass types compared to coal.

	Lower heating value (MJ/kg)	Moisture (%)	Ash (%)	Bulk density (kg/m^3)	Energy density (bulk)/GJ/m^3
Wheat straw	14.4	15	10.2	100 (bales)	1.4
Switchgrass	18.9	10–15	5.4–6.9	140 (bales)	2.2
Sawdust	15.2	6–30	0.5–1.1	160	2.4
Wood chips	17–18	30–55	0.7–10	200–450	2.2–4
Wood Pellets	16–17	5–10	0.4–1	550–700	7.8–10.5
Torrefied wood	19–23	1–5	<3	180–300	3.5–6
Torrefied pellets	19–23	1–5	<3	750–850	15–18
Charcoal	30–35	5–10	<6	170–220	5–8
Coal	17–33	6.5–12	10–40	800–850	25–40

Source: [27–32].

information on the characteristics and cost of delivered torrefied biomass is not consistent[1] [33,6,34].

This study aims to improve and add to previous work such as [24] by using more recent information and industrial experiences, extend the analysis by examining different types of biomass feedstocks and through detailed analysis of the mass and energy balance of the torrefaction process.

Overall, the goal of the study is to provide insights into state of the art prospects of the commercial utilization of torrefaction technology for biomass pretreatment, for both the short and long term. The study provides detailed insights into the economic performance of the compact moving bed reactor, and the impact of biomass feedstock characteristics as well as scaling and technological learning in equipment. For this reactor type, the study also identifies process performance characteristics such as thermal efficiency and mass yield[2] and discusses their determining factors through analysis of mass and energy balances. The characteristics of torrefaction concepts in this study are all based on laboratory, demonstration and pilot scale results, and the information is derived from scientific and grey literature as well as experts from industry.

This paper is organized as follows: Section 2 explores the development of torrefaction technology and discusses key technical aspects of state of the art torrefaction technology concepts. Section 3 presents results of energy and balance modelling and Section 4 evaluates the short and long term economic performance of the selected torrefaction concept. Section 5 deals with future performance trends in torrefaction technology. The paper concludes with a discussion in Section 6 and conclusions in Section 7.

2. Review of torrefaction technology

2.1. Background

Biomass has unique characteristics that necessitates preprocessing before it can be stored, transported or used in various applications. Unlike fossil fuels which are mined at one location,

Table 2
Biomass characteristics and required corresponding supply chain interventions (for thermal conversion).

Biomass characteristic	Improvements through torrefaction pretreatment
Low heating value (due to low fixed carbon content of about 45% and relatively high moisture content, typically about 50%). LHV of wet wood chips is about 7–10 GJ/tonne [28]	Increased fixed carbon: the fixed carbon content of torrefied biomass is high (25–40% depending on reaction conditions) [29,44,43]. Combustion properties: torrefied biomass burns longer due to larger percentage of fixed carbon [45].
Lower energy density than fossil fuels. E.g. the energy density of wood chips is about 2–4 GJ/m^3 compared to 25–40 GJ/m^3 for coal [28].	Densification: torrefied and pelletised biomass (TOPs) has high energy density of 18–20 GJ/m^3 [27]. It contains 40–80% of the original mass while retaining 80–96% of original energy of the biomass on a dry ash free basis[a] [46].
Hydrophilic and hygroscobic (absorbs moisture during storage and transportation)	Hydrophobicity: torrefied biomass becomes hydrophobic, i.e. it does not absorb moisture or its equilibrium moisture percentage drops [47,48]. The equilibrium moisture content of torrefied biomass is very low (from 1 to 3%) [49], but depends on the severity of torrefaction [48].
Heterogeneous characteristics (wide range of shapes, sizes and types) and quality [39]. This results in wide variations in combustion properties given the differences in fixed carbon, volatiles, inorganic constituents, moisture, calorific value; In addition, this variation causes handling and storage difficulties [50,32]. In gasification, the presence of volatiles in biomass yields tar which contaminates catalysts [10,42,51]	Torrefaction produces a solid uniform product, as volatiles and moisture are eliminated. On grinding, the particle size distributions, sphericity, and particle surface areas become similar to coal [3]. It also results in improved chemical composition making it more suitable for fuel applications [52]. Bridgeman et al. [45] and Chen et al. [53] show a reduction of sulphur and nitrogen content of torrefied straw and reed canary grass. Grassi [54] argues that torrefied biomass results in less HCl emissions.
Low combustion efficiency, smoking during combustion. Also for large scale cofiring applications, raw biomass has poor flowability, poor blending and reduces the thermal efficiency and capacity of existing boiler units [10]. Also volatiles cause equipment corrosion, slagging and fouling [55,56,51,57], increasing operational costs.	Reduced oxygen: torrefaction reduces the O/C ratio and this makes a biomass better suited for gasification [4,44,58]. Torrefied biomass also produces less smoke during combustion since smoke-causing volatiles are driven off during torrefaction [32,59]. Combustion properties: torrefied biomass takes less time for ignition due to less moisture [45].
Tough and fibrous, difficult to pulverize [60,61]	Improved grindability: torrefied biomass requires less electricity to grind compared to wood chips [62,63,13,64,22].
Biodegradable: due to moisture and environmental stresses, biomass typically degrades over time due to natural decomposition if it is not well protected [65]	Stable: torrefied biomass has very low moisture and can therefore be transported and stored for long periods without any biological degradation [59]. Removal of OH groups and formation of unsaturated structures renders biomass hydrophobic and resistant to biological degradation [21].
Small quantities scattered over many sources locations and seasonal availability [43]	Biomass can be torrefied and pelletised in decentralised locations and stored for long period without an impact on its quality [64]. Such pretreatment also improves the economics of transportation and handling biomass [66].

[a] The actual energy density of TOPs varies depending on biomass type and torrefaction process parameters such as torrefaction temperature, residence time, rate of heating, reactor type, etc. [68]. Ben and Ragauskas [40] achieved a higher heating value (HHV) of loblolly pine of 32.34 GJ/t at an energy yield of 59%, compared to an HHV of 24.06 GJ/t at an energy yield of 81% depending on process conditions.
Source: [46,32,1,67,50].

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[1] Most developers do not provide detailed reports on the performance of their technologies and optimisation of process conditions is still an on-going challenge [5]. There are varying claims on the hydrophobicity, stability and long term storage possibilities of torrefied pellets, even at same process conditions [33]. It is also not clear if densifying torrefied biomass is more costly than densifying pulverised wood. There is no detailed inventory of investment costs for existing technologies and it is difficult to compare investment costs since it is not known what costs have been taken into account in each case. For example, indirect costs, construction contingency, etc. may or may not be included in reported costs.

[2] While the final energy density of the product is a key attribute of the torrefied product quality, its mass and energy yield are important indicators of the performance of the torrefaction process. The mass and energy yields have implications for the economic performance of the torrefaction facility. To achieve the highest energy density of the torrefied biomass, a low mass yield and a high energy yield are desirable.

Table 3
Key technical performance indicators of torrefaction plants.

Performance	Low	Nominal	High	Units
Energy efficiency (energy yield)[a]	70	94	97	%
Feedstock to product ratio[b]	3.6	1.7	1.3	
Electricity use	158	171	254	kWh/t
Plant scale[c]			<250	kt/yr
Calorific value of TOPs (moisture content 1–5%)[d]	19	21.5	24	GJ_{LHV}/t
Volumetric density of TOPs[d]	12	15.1	19	GJ_{LHV}/m^3
Bulk density of TOPs[d]	650	750	850	t/m^3
Grindability (energy use for grinding torrefied biomass)[e]	10	25	350	kWh/t
Hydrophobicity[f]	<10	12	15	% wt saturated moisture content
Pelletability (energy required to densify torrefied biomass)[g]	8	22	45	kWh/t

[a] The energy yield is the fraction of the chemical energy contained in the original biomass that remains in the torrefied biomass on a dry ash free basis [72].

[b] Alternatively expressed as the reciprocal mass efficiency (or gravimetric yield) which is the fraction of the initial dry ash free mass of the biomass that remains after torrefaction [72].

[c] Current systems are limited to 200 kt due to feedstock availability limitations [73].

[d] The calorific value for torrefied biomass depends on the process conditions and exact values are likely to be influenced end-user requirements [74,75,2].

[e] Grindability of torrefied biomass depends on the severity of torrefaction. Using a Retsch SM 2000 laboratory heavy duty knife mill Phanphanich and Mani [3] give grinding energy for pine chips of 103 kWh/t (at 225 °C) and 24 kWh/t (300 °C); for logging residues energy required is 114 kWh/t (at 225 °C) and 38 kWh/t (300 °C); Using a Retsch SM1 knife mill with a 8 mm grid, Repellin et al. [12] give grinding energy for beech as 300 kWh/t (at 220 °C) and 100 kWh/t (at 280 °C), while for spruce the energy required is 350 kWh/t (at 220 °C) and 150 kWh/t (at 280 °C) using a RetschZM 1 centrifugal mill; Bridgeman et al. [13] use the Hardgrove grindability index (HGI) to evaluate the grinding energy requirements for willow and miscanthus at 290 °C for 60 min using a Retsch PM 100 ball mill. They give an HGI of 32/49 for willow and 66/92 for miscanthus. The HGI expresses the relative difficulty of pulverising coal to a particle size, the higher the HGI value the more easily a coal can be reduced to smaller sizes.

[f] Several experiments show that unpelletised torrefied biomass absorb water and up to moisture content of 10–15%. In pellet form the water absorption is lower and 24 h immersed fully in water still did not affect moisture content [76]. The impact of storing TOPs outside in a pile form for several weeks is still uncertain [23]. However according to [77,78,48] hydrophobicity depends on the severity of torrefaction and biomass particle size. Peng et al. [33] show the moisture uptake of torrefied pellets made from different size (0.23, 0.67 and 0.81 mm) torrefied pine sawdust and torrefied with different degrees of severity. The torrefied material is preconditioned to 10% moisture content for 24–72 h and densified at a die temperature of 100 °C. On exposure in the humidity chamber for 6000 h, the saturated moisture uptake decreased with increasing the degree of torrefaction. Torrefaction at 200 °C reduced water uptake marginally compared to ordinary wood pellets, while samples torrefied at 300 °C and with higher weight loss reduced the saturated water uptake from 18% to 12%, representing a 33% reduction.

[g] According to Stelte [79] current studies give conflicting views on the energy requirements for pelletising torrefied biomass. A number of studies that have analysed pelletization after torrefaction include [80–82,78,77,33] argue that more energy is required to pelletise torrefied biomass due to loss of lubricity when hemicellulose is destroyed. Hot pelletisation is an option which is not feasible with current technology due to fire risks and also because current pellet die lubricants would evaporate at torrefaction level temperatures. The pressures and energy required for densification can be reduced by a factor of two when material is densified at a temperature of 225 °C. The pellets that are produced have a higher mechanical strength, typically 1.5–2 times greater, than conventional wood pellets [52]. Consequently, the pelletiser capacity would require to be derated [83] and die life is shorter [2] to account for this additional effort. According to [77,78,33] there is a trade-off between pelletisation effort, torrefaction severity and pellet quality; severe torrefaction gives highly hydrophobic pellets, but these pellets are difficult to make. Mild torrefaction reduces the hydrophobicity and the grindability, but the pellet is easier to produce and stronger.

Table 4
Overview torrefaction reactors under development.

Reactor technology	Companies (developer)	Reactor technology	(Planned) capacity
Belt dryer	Agri-Tech producers LLC/RTF (US)[a]	Torr-Tech	5 ton/h
	4 EnergyInvest–AmelBiocoal (BE)[b]	Stramproy	38 kt/yr
	New Earth Eco Technology (US)[a]	Eco-Pyrovac	2 ton/h
	Stramproy Green Investment (NL)[a,b]	Stramproy	45 kt/yr
Rotary drum	Torr-Coal (NL)[a,b]	Torr-coal	35 kt/yr
	Andritz (AT)	ACB/ECN[c]	50 kt/yr
	Atmosclear (UK)/Airless (CH)[a]	CDS (UK)	50 kt/yr
	ETPC-Umea University (SWE)[a,b]	BioEndev	25–35 kt/yr
	Torkapparater (S)	–	100 kt/yr
	BIO3D (FR), Stramproy (BE), Earth Care Products (US), TSI (US)	–	–
Screw conveyer	BioLake BV/ATO (NL)[a]	BO_2/ECN	5–10 kt/yr
	BTG (NL)[b]	BTG	5 ton/h
	Foxcoal (NL)[a]	–	35 kt/yr
Multiple hearth furnace	CMI-NESA (BE)[a]	NESA	–
	Integro Earth Fuels LLC (US)[a]	Wyssmont	50 kt/yr
Compact moving bed	Buhler (GER)[a]		–
	ECN (NL)[a,b]	BO_2	5 ton/h^2
	Thermya (FR)[a]	Torspyd	20 kt/yr
Torbed (Rotating fluidised bed)	Topell (NL)[a,b]	Torbed	60 kt/yr
Microwave	CanBiocoal (UK)[a]	Rotawave	110 kt/yr
Hybrid	Airex (CAN), Torrefaction Systems (US)	–	–
Fluidised bed	River Basin Energy (US)	–	6 t/h
Other/unclear	BioTorTech (NL), Alterna (CAN), Ecotech/Sea2Sky (US), Energex (CAN), Torrproc (US), New Earth Renewable Energy Fuels (US)	–	–

Key: AT-Austria, BE-Belgium; CA-Canada, CH-Switzerland, FR-France; NL-Netherlands; GER-Germany; S-Spain, SWE-Sweden, UK-United Kingdom, US-United States of America.

[a] Source: [5,6], Company websites.

[b] Source: [75,87], Company websites.

[c] (ACN)-Accelerated Carbonised Biomass technology developed by EBES ABC Entwicklungs GmbH - demonstration plant operational at 1 ton/hr in Frohnleiten Austria; ECN design - demonstration plant at 1 ton/hr to be commissioned in Denmark in 2012 [88].

biomass is often available seasonally in small quantities scattered over many locations [35,16]. Biomass is highly heterogeneous in quality and nature, and is mostly available in low energy density form [36,37,3,38,39]. It has relatively high moisture content and consequently lower heating value compared to fossil fuels [40,41,9,39]. It therefore often needs to be pre-treated to improve handling [19,42,43]. Table 2 lists some of the key biomass characteristics and the corresponding preprocessing activity that is required to ensure biomass energy supply chains are competitive.

Torrefaction promises to deliver a solid biofuel which (when densified) has superior characteristics that are similar to coal in terms of handling, milling and transport [5,36,1,69,2,3]. This has potential to vastly improve the competitiveness of biomass as a renewable energy carrier (provided production costs decline over time following a typical technological learning curve). Over the last decade, the process of torrefaction has received renewed interest as a possible pre-processing technology for biomass [70,71,6,1] driven by a potentially huge market for biomass for electricity production through co-firing or converting coal power plants to biomass entirely [5,6]. Biomass is the only renewable resource that can directly substitute coal in many applications [1,69,2,3]. If torrefied biomass becomes a market success, it could become an important CO_2 mitigation option [46,55]. Table 3 shows the variation ranges in performance indicators for torrefaction plants including the nominal values used in this study.

Due to its potential attractiveness, torrefaction is being developed by more than 60 technology suppliers, developers and knowledge institutions [84,85]. About 30 projects are being implemented; mainly in Europe and North America [6] and four industrial scale projects are running [20]. At least 50 torrefaction

Table 5
Comparison of performance of moving bed reactor concepts under development.

Reactor type	Advantages	Disadvantages
Compact (moving) bed reactor	• Relatively simple and low cost reactor • High heat transfer • High capacity of the reactor able to support large biomass throughput • No moving parts in reactor • Can process biomass with lower density without large disadvantages	• Presence of dust particles cause high pressure drops, which can result in automatic reactor shut down • Limited biomass size and type due to pressure drop • Temperature distribution is not uniform, especially with indirect heating • Possibility for channel formation between biomass particles causing unequal torrefaction • Difficult temperature control • Scale-up potential is unproven
Torbed reactor	• Low residence time (<100 s) • Large throughput due to fast heat transfer and low residence time • Scalable technology (to 25 t/h) • No moving parts (low maintenance) • Ability to precisely control product	• High utility fuel demand[a] • Volumetric reactor capacity is limited • High temperature leads to a greater loss of volatiles • Risk of tar formation due to relative higher loss of volatiles
Belt dryer	• Better temperature control • Ability to take wide range of biomass sizes • Relatively low investment costs • Easy control of residence time through the speed of the belt • Proven technology from biomass drying industry	• The holes in the belt can become clogged with tar and dust, causing unequal torrefaction - torrefied product is not homogeneous • Limited upscaling potential since capacity is dependent on the surface area of the belt (other systems are volume dependent) • Limited temperature control • System has too many mechanical parts, which increases maintenance costs
Rotary drum	• Various methods to control torrefaction process. It can employ both direct and indirect heating • Uniform heat transfer • Ability to take wide range of biomass sizes and waste types • Proven technology for biomass drying	• Lower heat transfer • Poor temperature control • Increase of dust due to friction between biomass and drum wall • Limited upscaling ability. Maximum capacity is at 10–12 t/h input, or 5 t/h torrefied product • High cost and large footprint
Screw conveyer	• Relatively cheap reactor • Better biomass flow • Ability to take wide range of biomass sizes • Proven technology	• Unequal torrefaction as biomass that touches the reactor wall is heated relatively more – results in hot spots • Poor heat exchange because mixing of biomass is limited • Limited scaling potential as the ratio of screw surface area/biomass volume is less attractive with larger screws
Multiple hearth furnace	• Good heat transfer • Good temperature control • Ability to take wide range of biomass sizes • Scalable technology (7–8 m of diameter possible)	• Large size of reactor • Heat demand is met through gas consumption making process less sustainable and gas combustion leads to moisture production in the flue gas. This gives a lower efficient combustion of the flue gas
Fluidised bed	• Good heat transfer • Scalable technology	• Selective particle size • Slow temperature response • Excessive biomass attrition and loss of fines • Separation of bed solids and biomass
Microwave	• Radiation based heat transfer instead of convection and conduction • High heat transfer and fast torrefaction • Heat transfer less dependent on the size of the biomass particle - ability to use large size biomass • Good temperature control • Modular	• Unproven technology for drying or torrefaction of biomass - effects of rapid heating of biomass not known • Electric energy needed for process • Heating of biomass interior is not uniform • Requires integration with other conventional heaters to achieve uniform heating

[a] But according to [94], this reactor has low energy consumption.
Source: [6,5,94,46,75].

patents have been published over the past five years indicating growing investigation into the technology [46]. Table 4 shows the status of some selected key reactor technologies that have been under development over the past few years. Most of the plants that have been built for commercial production do not operate at their design capacities [86].

2.2. Reactor concepts and stages of commercialization

The majority of the torrefaction technologies being developed are based on already existing reactor concepts designed for other purposes such as drying or pyrolysis [89], and thus only require technical upgrading for torrefaction applications. Most torrefaction technology developers are companies with extensive backgrounds in biomass processing and conversion technology, such as carbonization and drying. The reactors being developed are in most cases established technologies that companies are familiar with and have been optimising for torrefaction applications. Currently, no single technique is fundamentally superior to the others as all of them have their advantages and disadvantages [6,75,76,90]. Proper selection of reactor is important as each reactor has unique characteristics and is well suited to handle specific types of biomass [46,91]. Therefore, for given biomass properties and application, the proper technology can be selected.

2.2.1. Choice of torrefaction reactor

Table 5 compares the performance of the eight common torrefaction reactors on the market, highlighting some of their key advantages and disadvantages. This study selected the state of the art technologies based on the extensive knowledge that is available on the compact moving bed reactor which has been under development by companies such as ECN and Thermya for numerous years. Unlike other reactor technologies, where very little information is in the public domain, several reports on the performance and

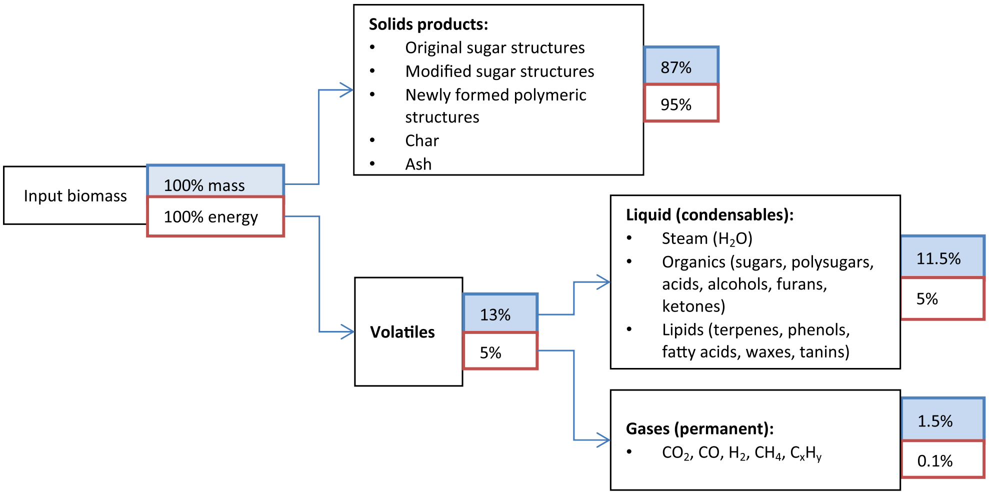
Solids products:
Original sugar structures
Modified sugar structures
Newly formed polymeric structures
Char
Ash
87%
95%
Input biomass
100% mass
100% energy
Liquid (condensables):
Steam (H_2O)
Organics (sugars, polysugars, acids, alcohols, furans, ketones)
Lipids (terpenes, phenols, fatty acids, waxes, tanins)
11.5%
5%
Volatiles
13%
5%
Gases (permanent):
CO_2, CO, H_2, CH_4, C_xH_y
1.5%
0.1%

Fig. 1. Distribution of torrefaction products (this distribution is specific for torrefaction of (dry) willow at a temperature of 250 °C (reaction time of 30 min) using the BO_2 process technology. Source: adapted from Refs. [60,74].

characteristics of the moving bed reactor have been published (e.g. Refs. [92,90,93,21,46]).

2.3. Production technology

Torrefaction is the thermal upgrading (heating) of biomass into an energy-dense and homogeneous product useful for further thermochemical conversions [95]. Torrefied biomass retains up to 96% of its chemical energy, becomes hydrophobic and resistant to biodegradation. Furthermore, biomass loses its visco-plastic properties, becomes brittle and can grind easily [96,61]. Torrefaction is carried out in inert environment (typically nitrogen) and normally under atmospheric conditions [40,7,61,65] – although some groups are experimenting with torrefaction under pressure e.g. Ref. [37] and in oxygenated environment e.g. Refs. [97,98] as well as in hot compressed water (so-called wet torrefaction[3]). During torrefaction, the more easily combustible components of biomass (i.e. hemicelluloses) are decomposed first and most vigorously, through carbonization and devolatisation. The mass loss of biomass is mainly due to this hemicellulose reaction [64]. Only minor decomposition of lignin and cellulose occur at torrefaction temperatures (200 °C–300 °C) but rate of decomposition depends on the type of biomass [99]. Their chemical structure is changed but no significant mass losses occurs [21,92].

Key torrefaction reaction products (of which the solid is of main interest) can be classified according to their state at atmospheric pressure and room temperature [30]. These include solids (in the form of char, original sugar structures and ash) and all the volatile compounds released during the process. The volatiles consist of condensables or liquids (mainly water, organics and lipids) and non-condensables or the permanently gaseous fraction (mainly CO and CO_2) [74,92,65]. See Fig. 1. The distribution of these products depends highly on the process conditions such as torrefaction temperature and residence time[4] [84,65].

2.3.1. Process techniques

Fig. 2 gives an overview of an integrated torrefaction plant. Incoming biomass is chipped to allow efficient drying and subsequent torrefaction. In the case of residues, the biomass is usually screened for impurities before sizing [84]. After sizing, biomass is dried to 20% moisture content and a small fraction of the feedstock biomass is used as fuel for the drying and torrefaction process. Direct or indirect heating with hot air, flue gas or steam are possible [75,84].

During the torrefaction process, moisture that is still contained in the biomass is driven out, as well as various low calorific components described before. In combination with the depolymerization process, this results in the end product of torrefied biomass. The gases leaving the torrefaction process can be divided into flue gases (mainly water and CO_2) and combustible gases merged under the name ‘torgas’. The exact composition of the torgas,[5] as well as the ratio between the torgas and flue gas, depend strongly on the type of biomass feedstock and the processing parameters [21]. The torgas is combusted together with a part of the biomass feedstock, generating heat for the drying and torrefaction process. However, torgas is difficult to handle as it contains water, tar and dust [100].

When the energy content of the torrefaction gases matches exactly the overall heat input requirements of the entire process, the torrefaction process is said to be running at the “point of auto-thermal operation” [21]. If the process is operated below auto-thermal operation, the additional energy needs to come from combustion of additional biomass feedstock. Operating the process above the point of auto-thermal operation reduces the overall thermal efficiency, as there is too much energy available from the torrefaction gas which cannot be fully utilized [101]. Consequently, the torrefaction process should be designed and operated closely below auto-thermal conditions to optimise the overall process thermal efficiency[6] and to improve the process economics. If torrefaction gas is insufficient to operate at autothermal conditions, additional biomass feedstock needs to be combusted or a utility fuel is added [66].

To enable densification, the torrefied biomass is pulverised before it is densified in a pellet mill.[7] A simpler rotor mill can be used for grinding instead of a hammer mill [102]. Currently, it is

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[3] Yan et al., [143], claim that wet torrefaction achieves greater energy densification than ‘dry’ torrefaction.

[4] Torrefaction products of lignocellulosic biomass are approximately 70–90% solids, 6–35% liquid, and 1–10% gases (on a mass basis) [91].

[5] Usually dominated by CO, acetic acid, methanol and 2-furaldehyde [21].

[6] Overall thermal efficiency depends strongly on the heat integration design through optimising the use of torgas [111,85].

[7] It is also theoretically possible to directly blend torrefied biomass (chips or power) with coal.

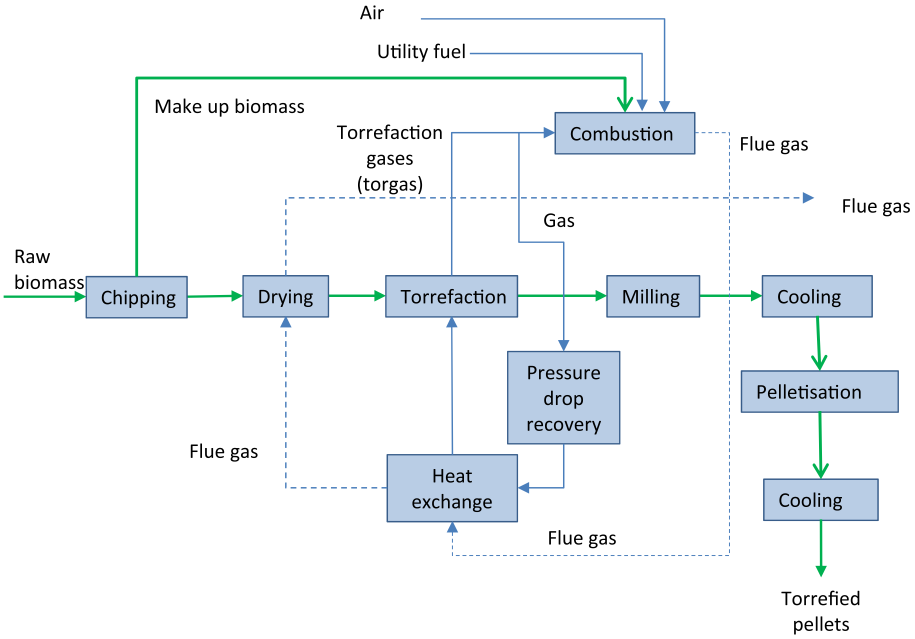

Fig. 2. Overview of an integrated torrefaction plant. Source: adapted from Ref. [74].

more efficient to allow the grinded biomass to cool before it is pelletised (cold feed). After pelletisation, the torrefied pellets are left to cool before being bagged or stored. It may be necessary to add a screening stage to check the product quality [84]. The presence of oxygen (outside the torrefaction reactor) and hot pulverised torrefied biomass poses fire risks [80,74], therefore cold feeding is necessary with current technology to ensure torrefied biomass is below safe self-ignition temperatures (below 130 °C) [103]. Hot feed (at e.g. 250 °C) could also lead to overheating of the pellet mill and melting of lubricants [80]. However, hot feeding would be more efficient as the thermally softened lignin at torrefaction temperatures acts a natural binder [79,104], since lignin undergoes relatively lower degradation at mild torrefaction temperatures [8,41,105]. Despite high lignin content, the low moisture content of torrefied biomass can increase the glass transition temperature of lignin and thereby affect its bonding properties [80,106].

2.3.2. *Technological challenges*

Despite global efforts to develop torrefaction technology, there are still several technical and economic challenges that need to be overcome before the technology is fully commercialised [20]. The torrefaction process itself is not fully understood scientifically[8] and the effects of reaction conditions are still being investigated [36,37,33,107,108,109,93,105,46]. However, significant progress has been made within a relatively short period, and the next few years can be considered a commercial demonstration phase for the technology [76]. For full commercialisation, torrefaction reactors still require to be optimised to economically meet end use requirements and achieve market standardisation of the product [6,76]. Certain characteristics need to be proven or scaled up in order to meet commercial expectations [23,110,96].

A major operation challenge is achieving optimum torrefaction process control of the biomass feed, process temperature and residence time to ensure optimal thermal efficiency and consistent torrefied product [89,6,100,20,65].

There is no scientific consensus on the hydrophobicity and grinding characteristics of torrefied biomass from current commercial scale tests [6,33,1,96]. These two characteristics are important in improving handling of biomass and competitive substitution of coal. The uptake of torrefaction technology in the utility industry will depend to a large extend on these two characteristics [11].

As a pre-processing technology, torrefaction technology's ability to accept a wider variety of heterogeneous biomass other than very clean woody biomass is very useful [34] in increasing the biomass resource base, especially if torrefaction can handle low cost agricultural residues (as ATO/Biolake is experimenting with[9]). Agricultural residues are problematic as they ignite easily, have lower density and long fibres [111]. Inconsistent biomass sizes also result in uneven torrefaction [2,75].

Currently, binding during pelletisation of torrefied biomass is done by adding steam or hot water [32,112,21]. Torrefied pellets may require additional binding material (e.g. glycerine, or dried distiller grain or soybean [70]), especially for severely torrefied biomass with high heating value [6,2,85] and this could as a result affect the sustainability of torrefied biomass[10] [2,111]. At current (demonstration and laboratory scale) production levels, there are inadequate quantities of torrefied biomass to test torrefaction products at a commercial scale [113,110,96,20].

Given the highly reactive dust [75], presence of flammable gases and need to operate in oxygen free environment [2], there are significant challenges for ensuring safety associated with self-ignition,[11] spontaneous combustion and dust explosions of torrefied biomass [85,74].

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[8] Torrefaction is a complex series and mixture of many endothermic and exothermic reactions [144,97,100]. Experiments are still being conducted to study the kinetics and pyrolytic behaviour of different types of biomass under different conditions using e.g. thermogravimetric (TGA) analysis (e.g. Refs. [107,47,108,105,42,68,65]). For some biomass types, exothermic reactions may occur at lower temperatures than expected [84].

[9] http://www.biolake.nl/

[10] Use of hydrophilic or chemical binders can result in end-use problems such as corrosion and fouling of boilers [145–147].

[11] Self-heating propensity depends on biomass type, torrefaction degree and end product (pellets or chips) [74,80].

Table 6
Impact of severity of torrefaction on biomass attributes.

Attribute	Degree of torrefaction		
	Light	Mild	Severe
Densification effort	++	-	—
Grindability of biomass	–	++	+++
Self-heating (propensity for)	+++	+	—
Heating value	—	++	+++
Reactivity (thermal stability)[a]	+++	+	—
Cost of production	+++	++	—

[a] Ref. [20] argues that the reactivity is actually diminished by torrefaction.
Source: Adapted from Ref. [74].

Although, significant efforts are made to identify optimum conditions for efficient and cost effective torrefied biomass, the effect of varying process conditions (e.g. particle size, residence time, process temperature and heating rate) is inconclusive [33,114,53]. For instance, a lower residence time enables a higher biomass throughput and lower process operational costs, but it does require smaller particle sizes to enable sufficient heat transfer to take place. This results in additional costs and energy use, and thus a trade-off and optimisation is required [111]. Also, severe torrefaction can yield a biomass product with a very high energy density >23 GJ/t. However, there is a trade-off in the energy density and the efficiency of the torrefaction system, benefits along the transportation chain and the desired characteristics at the final energy conversion plant [111,68]. Hence there is a need for identifying optimum conditions for torrefaction systems through ‘trial and error’ [83,85,76] and matching end-use requirements [89]. Kiel et al. [74] argue that mild torrefaction is preferable in most applications as shown by the simple rating in Table 6. Although severe torrefaction has higher heating value [68], it is not cost-effective while light torrefaction does not adequately improve the characteristics of biomass.

3. Mass and energy balance modelling

3.1. Methodology

The feed to product ratio and the thermal efficiency are key torrefaction performance indicators and need to be determined from the process mass and energy balance. A simplified[12] design of the balance is presented in Fig. 3.

In modelling the energy and mass balance, a number of process parameters (e.g. heating value of torrefied product, moisture content of biomass) need to be predefined while others are calculated as described below. An important outcome of the model is optimising the entire process to achieve high energy yields and feed to product ratio by effective utilisation of torgas heat. Biomass feedstock and air to the combustor are the input streams, while torrefied biomass and flue gas are the only output streams. The ash that remains after combustion is considered negligible (on both mass and energy basis) and is therefore not included in the mass and energy balance.

Modelling the mass and energy streams is not a straightforward calculation since there are feedback loops in the process (part of the flue gas from the combustion process eventually heads back to the combustor). The model is based on the principles of preservation of mass and energy, and is composed of a simplified theoretical model (based on [101]), adjusted by using confidential information[13] of the mass and energy flows of an existing pilot torrefaction plant and by specifying the feedstock characteristics. Critical adjustments made to the theoretical model using more detailed data include:

- More detailed estimation of the moisture content during the different steps of the process
- Adding efficiencies for the heat exchanges and different processing steps
- More precise calculation of the energy requirement for evaporating the water contained in the biomass
- Adjusting the torrefaction parameters such as the energy yield (energy ratio between the flue gas and torgas).

Key modelling steps:

- Establishing biomass feedstock characteristics (i.e. moisture content, heating value and volumes required for processing)
- Establishing the (desired) calorific value of the torrefied end product
- Establishing biomass moisture contents during process (after drying, after torrefaction)
- Calculating process efficiencies (combustion, drying and torrefaction)
- Calculating the thermal energy requirements for drying and torrefaction process
- Calculating the amount and energy content of torgas (to ensure process operates below the auto-thermal zone)
- Calculating the additional biomass feedstock combusted to fulfil the total thermal requirements of the facility
- Calculating the energy losses at various points in the facility (including heat exchangers, combustor, and flue gas stack losses)
- Calculating the energy content in the biomass at every stage of the facility
- Calculating the gravimetric and energy yield of the facility

Model calculations were performed using the solver option in Excel. The thermal efficiency of the balance was optimized by varying the percentage of biomass heading to the combustor. Parameters regarding the biomass feedstock characteristics were set in advance, as well as the calorific value of the torrefied biomass. Several process parameters such as the efficiencies of the process steps, air to fuel ratio of the combustor, heat demand of the dryer and characteristics of the torgas could be varied in the model. However, these parameters were set based on the knowledge from the mass and energy balance of the existing pilot torrefaction plant.[14] The process conditions used for modelling include temperature of 275 °C, reaction time of less than 60 min, heating rate of 50 °C per minute and biomass particle sizes of 20–30 mm.

3.1.1. Mass and energy balance equations

We present here the mass and energy balance equations that were used to model torrefaction of woody biomass. These flows are presented for the main processing components (i.e. drying, combustion and torrefaction) in simplified form.

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[12] In reality, the mass and energy balance design is more complicated than presented in Fig. 3.

[13] The actual modelling was much more detailed and complex than the core model and entailed adding and adjusting process parameters using industry and confidential practical data from an existing pilot plant as well as expert estimates.

[14] Publication of this data is not possible due to the confidentiality reasons.

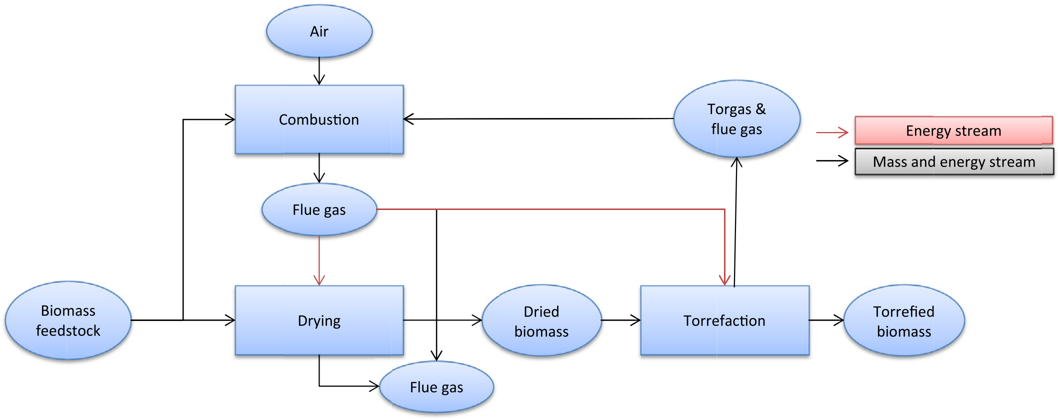

Fig. 3. Design of the mass and energy flows in the mass and energy balance of torrefaction. Processing steps are presented in the squares, actual mass streams are presented in the oval shapes.

Drying

Energy requirements for drying the biomass are supplied by combustion gases from the combustion isle. These combustion gases use part of the biomass stream as well torgas as fuel. However, to simplify the mass and energy balance, we estimate the thermal energy requirements drying using only the biomass component. Equation (1) below is used as the basis for estimating the dry biomass combusted (m_{tdbc}) to provide drying heat:

$$m_{\text{tdbc}} = m_{\text{tbi}} \times \left(1 - \frac{\text{mc}_i}{\text{mc}_o}\right) \times \left[\frac{1}{\left(\frac{B}{\text{LHV}_{\text{dry}}}\right) \times \text{mc}_o + (\text{mc}_o - 1)}\right] \times \frac{B}{\text{LHV}_{\text{dry}}} \times \text{mc}_o \times \frac{1}{\eta_{\text{dry}}} \qquad (1)$$

where m_{tbi} – is total annual biomass processed (tonnes)

mc_i – is moisture content embodied in wet biomass (%)
mc_o – is moisture content embodied in dried biomass (%)
B – is total dry biomass consumed per ton of water evaporated (2.5 GJ/twe)
LHV_{dry} – is the lower heating value of dry biomass (GJ/tonne)
η_{dry} – is the efficiency of the dryer

The energy required for drying (E_{dry} in GJ) is given by Equation (2):

$$E_{\text{dry}} = m_{\text{tdbc}} \times \text{LHV}_{\text{dry}} \qquad (2)$$

For the main biomass and flue gas streams, the mass balance is given by the following equation:

$$m_{\text{raw biomass}} = m_{\text{dried biomass}} + m_{\text{flue gas dryer}} \qquad (3)$$

where $m_{\text{raw biomass}}$ – is the raw biomass to be processed into torrefied material (tonnes)

$m_{\text{dried biomass}}$ – is the dried biomass (output of dryer) (tonnes)
$m_{\text{flue gas dryer}}$ – is the amount of flue gas emitted from dryer (tonnes)

The mass balance of the flue gas streams is given by:

$$m_{\text{flue gas}} = m_{\text{comb gas}} + m_{\text{flue gas dryer}} \qquad (4)$$

where $m_{\text{flue gas}}$ – is the total amount of flue gas emitted by the plant (tonnes)

$m_{\text{comb gas}}$ – is the amount of combustion gas produced (tonnes)

To calculate the energy balance of the flue gas streams (which represent total thermal energy losses of the plant), we use the following equation:

$$U_{\text{flue gas}} = U_{\text{flue gas dryer}} + Q_{\text{dryer}} + Q_{\text{comb}} + Q_{\text{torr}} \qquad (5)$$

where $U_{\text{flue gas}}$ – is the amount of energy in the flue gas emitted from plant (GJ)

$U_{\text{flue gas dryer}}$ – is the amount of energy in the flue gas from the dryer (GJ)
Q_{dryer} – are the energy losses from the dryer (GJ)
Q_{comb} – are the energy losses from the combustion isle (GJ)
Q_{torr} – are the energy losses from the torrefaction isle (GJ).

Combustion

All the process heat requirements of the plant are provided by the combustion isle using part of biomass stream and torgas as fuel. This thermal energy is supplied to the dryer and torrefaction reactor. Part of this energy is lost with the emitted flue gases as well as through the heat exchangers. The mass balance of the combustion isle is given by the following equation:

$$m_{\text{comb gas}} = m_{\text{tbc}} + m_{\text{torgas}} + m_{\text{air}} \qquad (6)$$

where $m_{\text{comb gas}}$ – is the amount of combustion gas produced (tonnes)

m_{tbc} – is the amount of biomass used for process heat (tonnes)
m_{torgas} – is the amount of torgas used for process heat (tonnes)
m_{air} – is the amount of air intake for the combustion process (tonnes).

The total combustion energy (which is corresponds to the total thermal energy requirements of the plant) is given by the following equation:

$$U_{\text{comb}} = \frac{U_{\text{tbc}} + U_{\text{torgas}}}{\eta_{\text{comb}}} = \frac{m_{\text{tbc}} \times \text{LHV}_{\text{dry}} + m_{\text{torgas}} \times \text{LHV}_{\text{torgas}}}{\eta_{\text{comb}}} \qquad (7)$$

where U_{comb} – is the total energy of the combustion gases (GJ)

U_{tbc} – is the total energy of the biomass used for process heat (GJ)

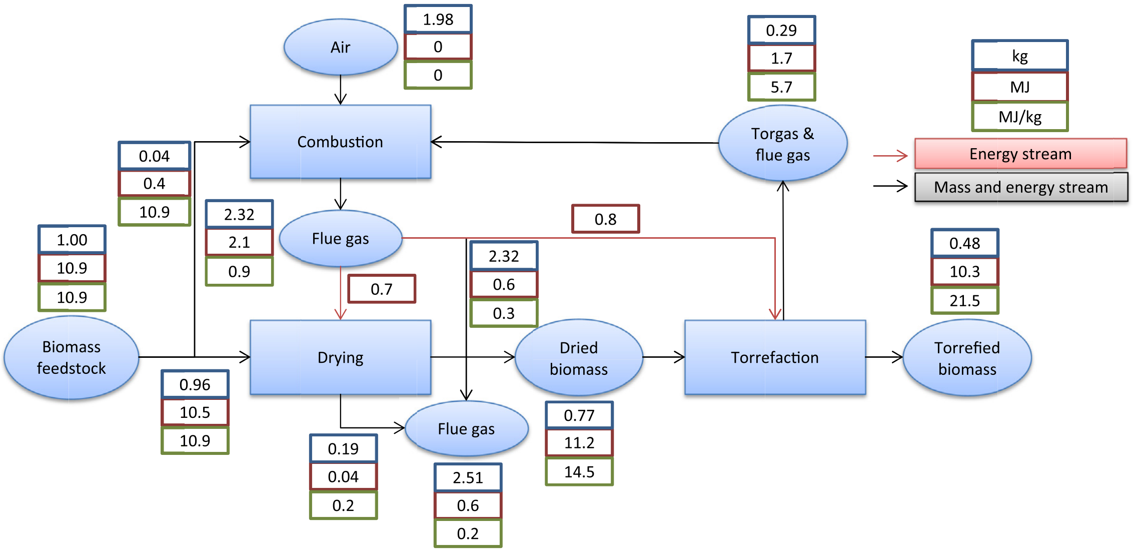

Fig. 4. Simplified energy and mass balance of integrated torrefaction facility with eucalyptus feedstock at 40% moisture content.

U_{torgas} – is the total energy of the torgas (GJ)
LHV_{torgas} – is the lower heating value of torgas (GJ/tonne)
η_{comb} – is the efficiency of the combustion device (%).

Torrefaction

The mass balance of the torrefaction isle is given in the following equation:

$$m_{\text{dried biomass}} = m_{torgas} + m_{\text{torrefied biomass}} \tag{8}$$

where $m_{\text{dried biomass}}$ - is the dried biomass input into the torrefaction reactor (tonnes)

m_{torgas} – is the amount of torgas produced during torrefaction (tonnes)
$m_{\text{torrefied biomass}}$ – is the amount of torrefied biomass produced (tonnes)

Energy requirements for torrefaction (ε_{torr}) are estimated as:

$$E_{torr} = \frac{\left(m_{\text{torrefied biomass}} \times LHV_{torr} - m_{\text{dried biomass}} \times LHV_{dry}\right) + m_{torgas} \times LHV_{torgas}}{\eta_{torr}} \tag{9}$$

where LHV_{torr} – is the lower heating value of torrefied biomass (GJ/tonne)

η_{torr} - is the efficiency of the torrefaction reactor (%)

Total system losses (U_{comb}) are represented by the difference between the total thermal demand of the plant (E_{comb}) and the effective energy used for drying and torrefaction as follows:

$$U_{comb} = U_{comb} - \left(E_{torr} + E_{dry}\right) = \frac{E_{torr} + E_{dry}}{1 - \eta_{comb}} \tag{10}$$

Mass and energy yields

The dry ash free (daf) mass and energy yields of the solid residues are calculated, based on the following equations:

$$Y_{mass}(\%) = \left(\frac{m_{\text{torrified biomass}}}{m_{\text{raw biomass}}}\right)_{daf} \times 100 \tag{11}$$

where Y_{mass} is the gravimetric yield on daf basis,

$$Y_{energy}(\%) = Y_{mass} \times \left(\frac{LHV_{\text{torrified biomass}}}{LHV_{\text{raw biomass}}}\right)_{daf} \tag{12}$$

where Y_{energy} is the energy yield of the torrefaction process on a daf basis.

When considering the torrefaction of other feedstocks, such as straw or switchgrass, the mass and energy balance changes. Due to the low moisture content of straw (15–20%), pre-drying of the feedstock becomes unnecessary. Therefore, for modelling straw, a similar process design has been used with the exception of the drying step. The biomass feedstock is directly torrefied, implying that heat is only demanded for this torrefaction process. However, because straw has higher ash content, heat losses may increase.

3.2. Results of mass and energy balance modelling

Results of modelling the mass and energy balance of the torrefaction process are shown in Figs. 4 and 5. All mass and energy balances represent steady state conditions reached after the start-up of the process. Initially, a larger part of the biomass feedstock needs to be combusted to generate sufficient heat for the drying and torrefaction process, since torgas is not yet available at the starting point. Results are separated for the different types of feedstock (wood and straw) that are analysed, since the mass and

Table 7
Product parameters for straw pellets and torrefied straw pellets.

Parameter	Pellets	TOPs
Calorific value (GJ_{LHV}/t_{dm})	13.8–14.5	17–18
Density (kg/m^3)	550–600	665–725
Sulphur content	0.24%	0.30%
Ash content	5.0%	6.3%

Source: [115].

energy balances of torrefaction differ to a large extent for these different types of feedstock.

3.2.1. *Eucalyptus as feedstock*

The mass and energy balance for eucalyptus is presented in Fig. 4. Of the biomass feedstock that enters the torrefaction plant, 4% is combusted directly to generate heat which is used for (pre) drying and torrefying the biomass. After the biomass is dried to 20% moisture content, torrefaction is applied until the biomass reaches the desired calorific value and moisture content. The released gas from the torrefaction unit (torgas) is combusted together with the part of biomass that is directly combusted to generate heat. The feedstock to product ratio can be derived from this balance, by dividing the mass of the biomass feedstock (1.0 kg) by the mass of the torrefied biomass (0.48 kg), resulting in a feedstock to product ratio of 2.10. The thermal efficiency can be calculated by dividing the thermal output (10.3 MJ) by the thermal input (10.9 MJ), matching an efficiency of 94%.

3.2.2. *Straw as feedstock*

Straw has a low bulk density ($<100\ kg/m^3$). The low moisture content (20%) enables a torrefaction process in which the pre-drying step can be left out. The higher sulphur and chlorine concentration however might affect parts of the process and equipment. In combination with the lower calorific value, this makes a high calorific output (in terms of GJ/tonne) difficult. Theoretically, also straw can be torrefied until a calorific value of 21.5 GJ/tonne is reaches. In practice, this is not likely as the corresponding torrefaction reaction time increases which in turn decreases the thermal efficiency. Therefore, the mass and energy balance model has been used to determine the optimal calorific value of torrefied straw. The model showed that a calorific value of 17–18 GJ/tonne is feasible without decreasing the thermal efficiency of the process, but since there is little experience with torrefying straw, the quality of the TOPs is not known. The characteristics of torrefied straw pellets (and of conventional straw pellets) are presented in Table 7.

When assuming a similar plant design, the mass and energy balance of torrefying straw can be presented as in Fig. 5. As a direct result of the pre-drying step becoming unnecessary, only 1% of the initial biomass is needed for heat generation. Therefore, the thermal efficiency increases to 96% (11.5 MJ/12 MJ), and the feedstock to product ratio is much lower when torrefying straw, namely 1.55 (1 kg/0.65 kg).

3.2.3. *Effect of moisture content on product ratio (woody biomass)*

The feedstock to product ratio is affected by the moisture content. Table 8 and Fig. 6 presents both the theoretically feasible feedstock to product ratio and the thermal efficiency as a function of the moisture content, as well as the modelled[15] outcomes of the mass and energy balance for wood with a calorific value of 17.5 GJ/tonne. Curves are only presented for feedstock with a moisture content in the range of 20–60%, since the torrefaction of feedstock with a lower moisture content is performed using a different process design (drying step becomes unnecessary), and biomass feedstock with a moisture content higher than 60% is almost always air-dried first before it is processed. One can see that the theoretically feasible product to feedstock ratio for torrefaction process (1.35–3.6) is higher than for the pelletisation process (1.2–2.9), and the theoretically feasible thermal efficiency for torrefaction (94–98%) is slightly below the efficiency of pelletisation (96–99%). The feedstock to product ratio results from modelling with actual plant data[16] (1.6–3.6) are slightly above the theoretical achievable ratios, and converge at higher moisture content. However, the modelled thermal efficiencies (86%–96%) are much lower compared to the theoretical values. This is mainly the result of lower efficiencies assumed for the dryer and torrefaction unit, as well as the addition of energy losses in the heat conversion processes (these equipment efficiencies are confidential).

3.2.4. *Effect of moisture content on product ratio (straw)*

The feedstock to product ratio and thermal efficiency as a function of the moisture content for both torrefaction and pelletisation of straw is presented in Table 9 and Fig. 7. Curves are only presented for feedstock with moisture content in the range of 10–25%, since straw with is very unlikely to have lower or higher moisture content. Similar to the processing of woody biomass, the torrefaction process has a higher feedstock to product ratio and lower thermal efficiency.

If the moisture content of the feedstock exceeds 20%, this would strongly affect the mass and energy balance. Torrefaction efficiency decreases dramatically if the biomass that enters the process has higher moisture content. Therefore, if the moisture content of straw is over 20% either the thermal efficiency decreases, or the addition of the pre-drying step is required again. Similar results were also obtained by Sha et al. [66].

4. Economics of torrefaction

Since torrefaction is an emerging technology, estimation of investment costs uses the factorial approach where cost components are estimated using factors and percentages on the basis of the purchased equipment cost (following [102,116,117]). For new technologies, cost estimates are highly uncertain due to unexpected implementation challenges [118] and thus additional indirect costs need to be accounted for to cater for unforeseen contingencies. However, despite these uncertainties, costs of major pieces of equipment are to a great extent known and these offer the basis for reliable production cost estimates [116].

4.1. *Lifetime*

There is no consensus on the lifetime of torrefaction plant. None of the pilot plants have operated for long enough time to determine the extent of wear that takes place, or the maintenance and repair required. In general it is assumed that the equipment should be able to last for a period of 15 years [119]. This is the same lifetime for pellet plants currently operating. Conservative studies are however using a lifetime of 10 years [21,120,24], to reflect the depreciation of drying and reactor equipment, which dominate investment costs [21]. Mul [120] estimate the lifetime of dryers and pelletizers to be typically 15 years. Grotheim [121] also indicate a

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[15] The formulae used in the calculations are presented in Section 3.1.1.

[16] This plant data is confidential and can therefore not be elaborated in this paper.

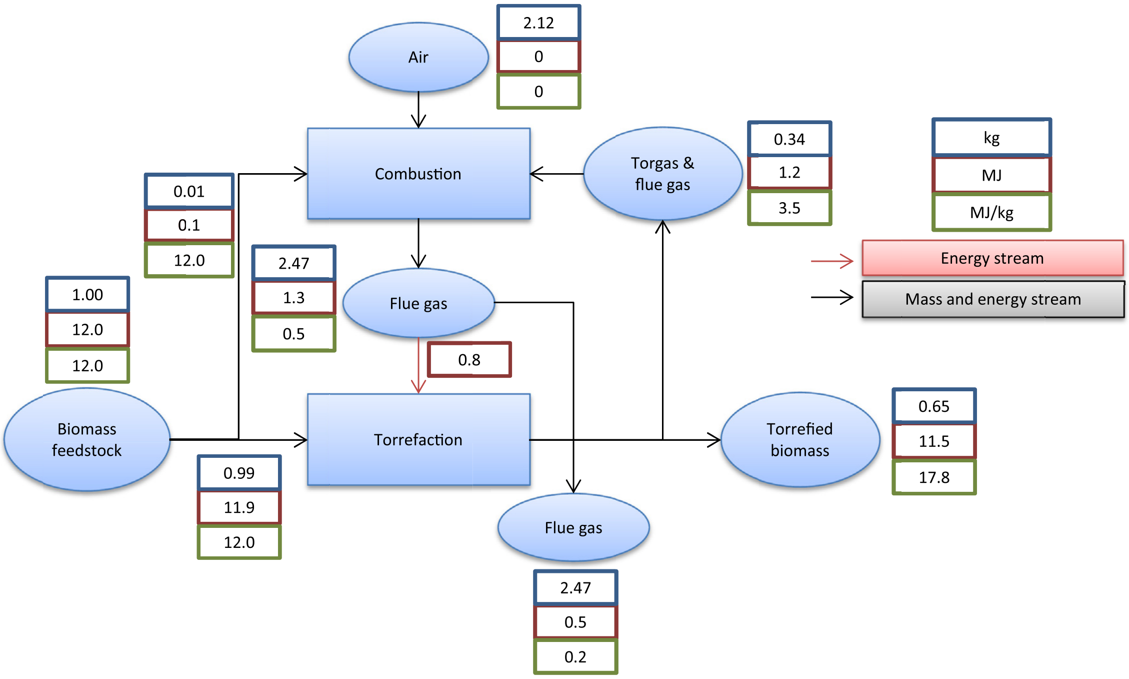

Fig. 5. Simplified energy and mass balance of an integrated torrefaction facility with straw feedstock at 20% moisture content.

depreciable economic life of process equipment (i.e. chipper, hammer mill, dryer, reactor, pellet mill) of 15 years.

It is unclear if operational costs for pelletisation of torrefied biomass are lower than for conventional pellets [37,70,50,79]. However, many recent studies increasingly suggest that pelletising torrefied biomass requires much more energy as the lubrication characteristics of hemicellulose and cellulose are destroyed during torrefaction [80–82,78]. Consequently, the pelletiser capacity would require to be derated [83] and die life is shorter [2] due to high friction in press channel and higher wear on the pellet mill parts [83]. Briquetting is also being investigated as it has potential to reduce densification effort [73].

4.2. Scaling factor

Scaling up the torrefaction reactor is expected to lower investment costs as relatively less material is needed for a larger capacity. A corresponding scaling factor can be derived which gives the proportional decrease investment costs for increasing capacity installations, and expressed as follows:

Table 8

Relation between feedstock to product ratio and thermal efficiency and biomass moisture content (eucalyptus).

Moisture content	Model values (torrefaction plant)		Theoretical[a] values (torrefaction plant)		Theoretical values (wood pellet plant)	
	Thermal efficiency	Feedstock to product ratio	Thermal efficiency	Feedstock to product ratio	Thermal efficiency	Feedstock to product ratio
20%	96.4%	1.59	98.0%	1.35	98.8%	1.19
30%	95.4%	1.84	97.6%	1.70	98.4%	1.4
35%	94.8%	1.99	97.3%	1.88	98.2%	1.53
40%	93.8%	2.18	96.9%	2.11	97.9%	1.69
45%	92.7%	2.41	96.3%	2.35	97.5%	1.89
50%	91.0%	2.72	95.6%	2.67	97.1%	2.14
55%	88.6%	3.11	95.0%	3.08	96.5%	2.47
60%	85.5%	3.59	94.1%	3.57	95.7%	2.92

[a] The theoretical values are calculated by assuming that there are no energy losses in the processes.

$$\frac{\text{Costs}_{\text{size 2}}}{\text{Costs}_{\text{size 1}}} = \left(\frac{\text{Size}_2}{\text{Size}_1}\right)^{\alpha} \tag{13}$$

where α is the scaling factor ranging between 0 and 1.

Since commercial industry players are operating their first torrefaction facility, no precise scaling factors are available from existing projects. However, basic principles behind scaling can be used to estimate the scale factor for increasing reactor designs based on the different rates of increase of area and volume of reactors.

Some reactor designs are limited in their scaling possibilities. For example, a screw reactor with a diameter above 40 cm causes a significant decrease in heat transfer and a high increase in material costs[17] [5,29]. Rotary drum reactors, as used by Umea University can be scaled up to 120 kt/year [122].

All other components of a torrefaction facility are based on existing equipment and thus their scaling factors are well known [89]. Thus, the hypothetical cost reduction with upscaling of the torrefaction facility, apart from the reactor itself, can be carried out in the same manner. Bergman [21] and Uslu et al. [24] are the only studies that attempt to analyse the scale factors of torrefaction facility components.

Above 12.5 tonnes/hr (current maximum reactor scale) capacity, multiple units need to be installed in parallel to achieve the desired capacity. In this study we also show the impact on the economics of torrefaction for plant scales of 50, 100, 250 kt/yr in the short term and scaled up to 500 kt/yr in the long term.

Overall, a scaling factor of 0.7 is used for the state of the art torrefaction system. This scaling factor takes into account the subcomponents that can be scaled up relatively easily (a dryer or storage silo) and other components which cannot. This figure compares well to other studies e.g. Refs. [21,24] which use an average scale factor of 0.63. A key difference is that a chipper and pelletizer are missing from the system of [21,24].

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[17] Scaling potential is limited since the ratio of screw surface area/biomass volume becomes less attractive with larger screws [5]. Bergman and Kiel [29] estimate the maximum capacity of screw reactor plants to be around 50–60 kt/yr.

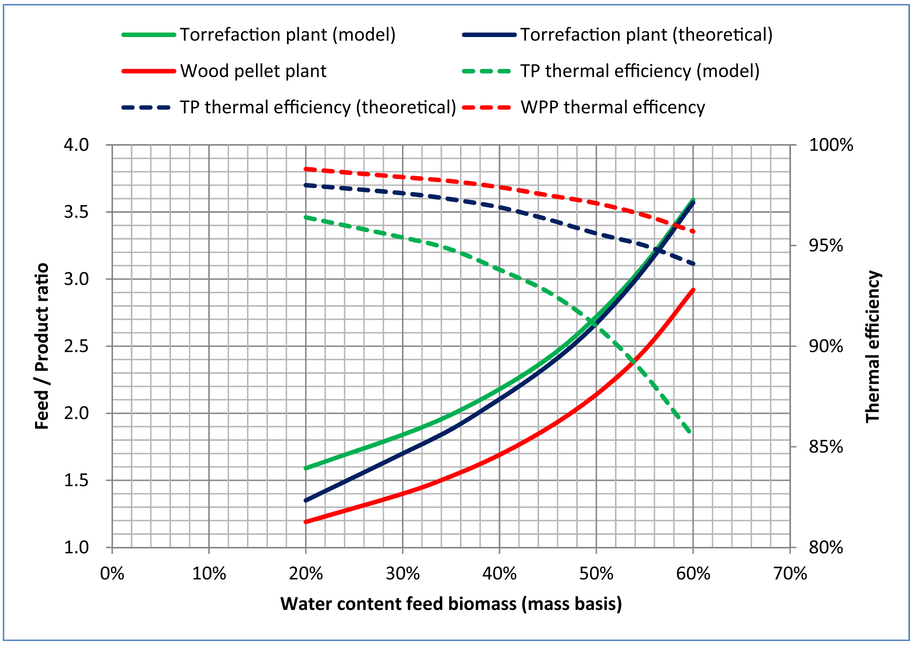

Fig. 6. Relation between feedstock to product ratio and thermal efficiency of the torrefaction process (*y*-axis) and the moisture content (*x*-axis) using eucalyptus wood as feedstock.

4.3. Torrefaction cost data

For a torrefaction production facility, the capital expenditure (Capex) consists of constructing the whole pre-processing facility, including the torrefaction reactor. This includes direct costs such as bare equipment and installation while indirect costs include the engineering design of the plant, supervision, fees and contingencies. Annual costs, (I_a) are calculated using the following formula:

$$I_a = I \times \frac{i}{\left(1-(1+i)^{-N}\right)} \tag{14}$$

where I – the total initial investment requirement ($)

i – the discount rate (%)
N – the lifetime of the facility (years) [117]

The operational expenditures (Opex) include the energy costs, labour, maintenance, rent, insurance, taxes and depreciation (Table 12). Biomass feedstock cost is excluded. Opex is expressed as a percentage of Capex. Table 10 below gives the general economic parameters assumed in the study.

4.3.1. Capex data

Tables 11–13 gives an overview of publicly available investment figures from demonstration and current pilot plants. It remains an arbitrary question whether one can compare these figures with one another as it is not known what costs have been taken into account and which ones have not. For example, construction contingency, the risk of financing the project (and thus cost of capital), management of the construction project and assigned a contractor might or might not be included.

Table 9
Relation between feedstock to product ratio and thermal efficiency and biomass moisture content (straw).

Moisture content	Model values (torrefaction plant)		Theoretical values (straw pellet plant)	
	Thermal efficiency	Feedstock to product ratio	Thermal efficiency	Feedstock to product ratio
10%	96.6%	1.37	99.0%	1.05
15%	96.4%	1.45	98.9%	1.1
20%	96.0%	1.55	98.8%	1.19
25%	95.7%	1.65	98.6%	1.30

4.4. Scaling up torrefaction facilities

Table 14 shows the results of applying the varying scales and subsequent production costs for torrefied pellets at today's technology.

5. Outlook on future torrefaction system performance

Although available knowledge is limited, estimation of the future cost development of torrefaction technology can be estimated using the technological learning concept. Considering the long term timeframe up to 2030, it is most likely that the torrefaction production processes will improve and that more plants will have been built. Numerous studies [130,131,102] have shown that as cumulative installed capacity increases the costs for installing a specific capacity decrease. The rate at which costs decline for every doubling of cumulative capacity is expressed as the learning rate [132]. For torrefaction technology, a learning rate can also be estimated for future cost analysis. The extent to which technological learning has effects on the cost of production in 2030 depends on the assumed learning rate and the cumulative installed capacity which can be achieved in the period up to 2030. We consider specific cost reductions through upscaling (scale-dependent learning[18]) as an integral part of overall cost reductions over time.

Currently, there are about 60 torrefaction initiatives worldwide, at different commercialization stages [6,20]. The total capacity of 12 of the planned initiatives amounts to 500 kt/yr which are expected

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[18] Scale-dependent learning are the reductions associated with economies of scale only (as depicted in Equation (13)), whereas scale-independent learning are the improvements through technological process development, efficiency improvements and process optimization [102].

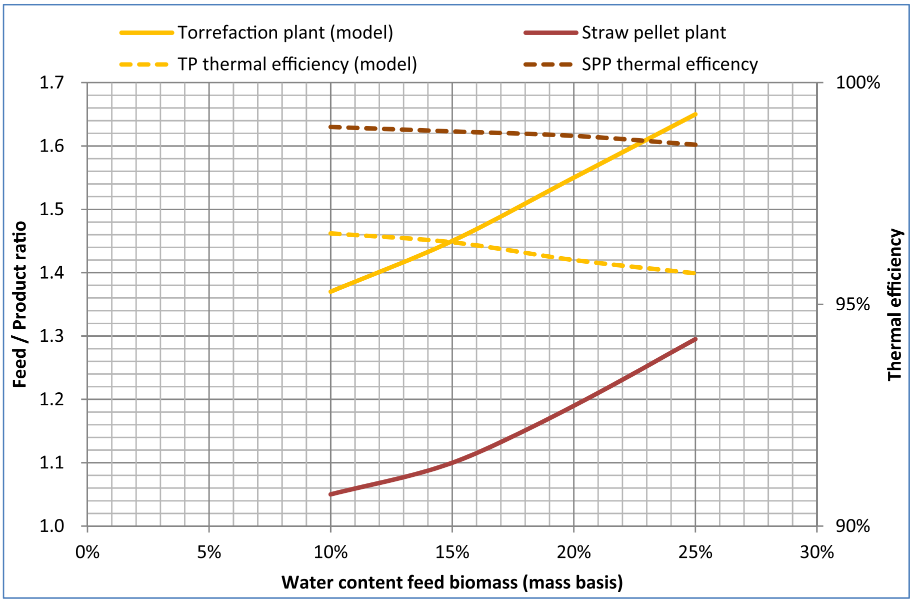

Fig. 7. Relation between feedstock to product ratio and thermal efficiency of the torrefaction and pelletisation process (*y*-axis) and the moisture content (*x*-axis) using straw as feedstock.

to be operational by 2015 (pre-learning phase). It is possible that during the early commercialization of technologies, costs may actually increase instead of decrease ([133,134,118,102]). This is because of uncertainties in initial cost estimations for scale up of pilot and prototypes [133,118,20]. This leads for example to high contingency costs. Only after the installation of a commercial scale unit that is operated at its stated capacity can the optimization of the design effectively take place. We expect this phase to be reached in 2015.

5.1. Increase in installed capacity (doublings of installed capacity)

The extent to which the learning rate has an effect on the costs by 2030 depends on the increase in installed capacity (represented by the amount of doublings of installed capacity compared to the base year). Future capacity is also affected by the cumulative use of individual system components in other industries (e.g. dryers and pelletizers are also used in the food industry). To estimate the cumulative installed capacity, a conservative approach is employed in this study as presented in Table 15.

Based on estimations by Sikkema et al. [135] by 2030 wood pellet facilities will have doubled in capacity by 2–3 times. Torrefied pellet facilities will have increased from the starting base of 0.5 Mton by end of 2015 to 20–28 Mton by 2030. The approach is modest in that it assumes that Torrefied pellet plants are only suitable for large scale power production, and that only 25% of pellet plants will feature torrefaction reactors. However, it is expected that most pellets plants would be converted into integrated TOPs facilities if torrefaction is successfully commercialised [139,140].

Table 10
General economic parameters.

Item	Value	Units
Interest rate	8%	%
Exchange rates	1.3	(US$/€)
Electricity costs	50	(US$/MWh)

Source: [27] – assuming plant in located in Finland.

5.2. Estimation of the learning rate

The majority of the components for torrefied pellet production have already widely been used in the wood pellet industry, as well as in other industries. Most reactors are mature technologies and apart from optimising process control, not much learning is expected inside the reactor. Optimisation is however expected in heat integrating of the torgas loop including the biomass/torgas combustor and condensers, waste heat utilization, inert nitrogen gas feed, moderation of exothermal reactions, fouling and maximising overall efficiency as well as addressing other challenges discussed earlier [20,6,89,76]. Following de Wit et al. [132], we use a scale-

Table 11
Investments and capacity of selected torrefaction facilities.

Company/Institute	Capacity		Investment costs		Status
	(kt/yr)	(t/h)	(mUS$)	(mUS$/t/h)	
Ebes/Andritz[a]	10	1	5.1	5.07	Pilot
Thermya[b]	20	2–3	5.2	2.08	Demonstration
4Energyinvest[c]	42	5–6	16.9	3.07	Pre-Commercial
Topell/RWE[d]	60	8	19.5	2.44	Pre-Commercial
Torr-coal group[e]	70	9	22.8	2.53	Pre-Commercial
UMEA University[f]	30	4	14.3	3.58	Demonstration
Industry average[g]				1.56–2.34	Commercial estimate
Industry average[h]				1.3–1.95	Commercial estimate

[a] 1 t/h pilot plant in Frohnleiten, Austria.

[b] Demonstration plant (2–3 t/h) in Northwest Spain together with IDEMA, group Lantec.

[c] Plant in Amel, Belgium. Operated through subsidiary Renogen. Stramproy initially started building the plant in February 2009 but it was terminated in June 2010. 4 EnergyInvest is now managing the project and looking to ramp up production in 2011 (Annual report 2010, 4 EnergyInvest).

[d] 8 t/h facility in Duiven, Netherlands -commercial ramp up takes place in 2011/2012.

[e] Plant located in Rotum, Belgium -is not operating at maximum capacity yet.

[f] Demo plant in Örnsköldsvik, Sweden. Construction in 2011 and operation in 2012 [122].

[g] Estimate [23]. This reference is from an industry expert.

[h] Estimate [120]. This is a full study which is based on various sources including industry experts and grey literature.

Source: [a–e] [123] (This reference is a periodic magazine that analyse pellet market trends. Investment figures are derived from industry experts)

Table 12
Operation and maintenance costs of torrefaction facilities (excluding feedstock) as reported in different studies.

Reference	Opex (% of Capex)	O&M and depreciation costs (US$/GJ) Excludes biomass feedstock costs
Industry experts estimate[a]	8%	3.3–5.9 (for systems capacities from 50 kt/yr-250 kt/yr); 4.8 (100 kt/yr)
Bergman [21],[b]	Not available	3.8–4.2 (45 kt/yr)

[a] Estimates derived from torrefaction industry experts.
[b] Equipment based cost estimation of torrefaction facility. Figures are inflation adjusted to 2012.

independent learning rate of 2% by taking the learning rate of second generation biomass to liquid plants (BtL) as a proxy for integrated torrefaction plants. This is a conservative estimate, but realistic considering the 15 year period that we are projecting our capital cost estimates. In addition, scaling effects have a much stronger impact on specific cost reduction than scale-independent learning [131] and are likely to be decisive in expected cost reduction.

Based on the assumed learning rate and scaling effects the following production costs for torrefied pellets might be obtained in the future (Table 16). The costs shown below exclude biomass feedstock costs.

Fig. 8 shows the cost development of torrefied pellets expected by 2030. We illustrate the impact of scale dependent learning as well as scale independent learning. In addition, we illustrate the significance of the pre-learning phase in which production costs for the first commercial plants (currently being implemented) increase before full commercialisation occurs. This phenomenon which is expected to last until about 2015 is due to unexpected performance shortfalls, uncertainties in scaling up prototype plants and unforeseen challenges during full scale construction and operation [102]. Using experiences from other technologies, we estimate that production costs may increase by up to 20% during the pre-learning phase, before technological learning begins [102].

Current TOPs conversion costs are estimated at 4.6 $/GJ at a scale of 50 kt/yr and are expected to increase to 5.8 $/GJ by 2015 in the pre-learning phase. Thereafter, cost reduction can be expected due to technological learning. Scale dependent learning has potential to reduce production costs by 23%, 38% and 50% for scaling up to 100, 250 and 500 kt from 50 kt capacity respectively. Scale independent learning is estimated to reduce costs by a further 11% from 3.6 to 3.2 $/GJ at a scale of 250 kt/yr, giving an aggregate cost reduction of 56% as shown in Fig. 8. Although, scaling up to 500 kt/yr is technically feasible, economically feasible systems have maximum designs of 250 kt/yr capacity [73]. In principle, cost reduction to 2.6 $/GJ at 500 kt/yr is also possible.

Table 14
Economic characteristics of torrefaction plants (2012).

Cost item	Scale of plant (thousands of tonnes of TOPs)				Units
	50	100	250	500	
Capex	23.4	38.1	72.3	117.5	M$
Capex/yr	2.7	4.4	8.4	13.7	M$/yr
Opex/yr	1.9	3.0	5.8	9.4	M$/yr
Electricity cost	0.3	0.5	1.4	2.7	M$/yr
Production costs	97.7	80.4	66.2	51.7	$/tonne
Production costs (excluding feedstock costs)	4.8	4.0	3.3	2.6	$/GJ

Apart from a reduction in production cost over the time, the characteristics of produced pellets might also improve. The process can be become more efficient on a technical level, such that higher energy density levels might be achieved at an acceptable feedstock cost. The demand of the final user (in this case utility companies) will determine exactly how the characteristics of the product will develop over time, i.e. through experimentation, the optimal energy density of torrefied pellets to co-fire with coal can be found.

6. Discussion

6.1. Data quality

Since torrefaction for large scale bioenergy production is currently being developed, there is limited documentation on its techno-economic performance and as a result, most of the data used in this study is based on grey literature, and also interviews and industry knowledge that is confidential. Given the sensitivities surrounding proprietary techno-economic data, companies and technology developers are generally reticent about sharing actual information, and thus the level of detail presented in this study is limited. It is important to take into perspective that the data sets used in this study are all based on demo, pilot and pre-commercial facility runs. Also, as the technology is rapidly evolving, the datasets are highly dynamic during this pre-commercial phase as companies are optimising their production processes for commercial scale operations. For example, considering the difficulties in obtaining efficient heat transfer at the Torr-coal, Topell and Stramproy plants, it is likely that actual energy efficiencies are lower than the values currently being reported. Shah et al. [66] use an efficiency of 60% for the torrefaction reactor, torgas combustor and heat exchange.

Table 13
Economics of integrated torrefied pellet production system at scale of 250 kt/yr (compact moving bed system).

	Base scale (t/h)	Max scale t/h	Base cost MUS$	O&M costs MUS$	No of units	Scale factor	Total invest MUS$	Energy costs MUS$	Annual costs MUS$
Chipping (Chipper)[a]	5	80	0.07	0.12	2	0.6–0.70	0.61	0.19	0.38
Drying (Rotary drum type)[b]	6	50	0.44	0.11	9	0.65	3.75	0.26	0.81
Torrefaction reactor (moving bed reactor)[c]	5	12.5	4.4–6.25	2.65–3.77	4	0.72	33.1–47.03	0.48	7.00–10.11
Milling (hammermill)[b]	5	50	0.07	0.022	1	0.70	0.37	0.073	0.15
Pelletising	5	20	1.46	0.41	7	0.61	10.18	0.359	1.96
Pellet mill			0.013						
Cooler[d]									
Bio-CHP boiler[e]	–		–	–	–	0.62–0.74		–	–

[a] [124], Vogel et al. [125] give estimates for costs for a chipper with a base scale of 500 m^3/h at 0.48 M€, scale factor is 0.6.
[b] [126,127]. For a belt dryer Staufer [128] gives a scale factor of 0.6 for a 20 t_{wb}/hr output Swisscombi Belt Dryer system. Swisscombi estimates that cost reduction due to economies of scale in the order of 5–10% are achievable with its technology. Based on 2003–2011 installed capacity the technological learning rate for belt dryers is 12%. On the other hand, Trattner [129] provides a scale factor of 0.25 for a 56 t_{wb}/hr maximum output Andritz Belt Dryer system.
[c] Uslu et al. [24] gives maximum scale for ECN's compact moving bed reactor at 12.5 t/h and scale factor of 0.72. Pommer [122] indicates the Umea university rotary drum dryer reactor can be scaled up to 15 t/h.
[d] Processco (2012)–www.processco.net/pellet-mills.php; Staufer [128] gives a scales factor of 0.7 for a Swisscombi pelletizer with a maximum scale of 40 t/h.
[e] For comparison, scale factor is specifically for the boiler; the scale factor of a Bio-CHP project based on Engineering Procurement and Construction is 0.81 [130].

Table 15
Estimation of growth in torrefaction capacity by 2030.

Torrefaction reactor	2010–2015[a]	2020	2030	Total doublings
Added capacity (Mt)	0.5	7.0–8.0	19.5–20.5	
Total capacity (Mt)	0.5[a]	7.5–8.5[b]	27.0–28.0[c]	
Number of capacity doublings	–	4	2	4–6
Other components	2010	2020	2030	Total doublings
Added capacity (Mt)	–	50–60	50–60	
Total capacity (Mt)	28[d]	70–80[e]	120–140[f]	
Number of capacity doublings	–	2	1	2–3

Year shown is the year after which the maximum cumulative capacity is reached.

[a] Pre-learning phase: 0.5 Mt capacity is expected to be installed by 2015. This figures accounts for all the reactor technologies. Not all announced projects are taken into account-some planned projects may fail.

[b] Wood pellet demand is divided between use for small-scale residential heating (bulk and bags), medium-scale district heating and for large scale power production (including CHP). The respective shares for the three uses is assumed as follows in EU-27: 40%, 20%, 40% in 2010 and 33%, 22% and 44% in 2020 [135]. This study assumes torrefied pellets will primarily be introduced for large scale power production, and that by 2020 only 25% of that figure will feature torrefied pellet production processes.

[c] Figure linearly extrapolated. Share between 3 uses is still assumed: 33%, 22% and 44%. Torrefied pellets production for large scale energy purposes will account for 50% of installed capacity (from 25% in 2020).

[d] US 6 Mtonnes, Canada 2.5 Mtonnes, Europe, 19.9 Mtonnes [136].

[e] Based on the scenarios by Sikkema et al. [135]. Consumption level in EU could increase to 35 Mtonnes by 2020. Assumption is that EU has 80% of global consumption [137] and that utilization rate of 54% of pellet production capacity in EU is maintained on a global level [138].

[f] Linear extrapolation from 2008 to 2020 figures.

Table 16
Estimated future torrefied pellets production costs by 2030 (assuming 6 capacity doublings).

Cost item	Torrefaction capacity (kt/yr)				Units
	50	100	250	500	
Capex	22.7	36.7	69.1	109.8	M$
Capex–adjusted to reflect pre-learning uncertainties	27.3	44.0	83.0	131.8	M$
Capex/yr	3.2	5.1	9.7	15.4	M$/yr
Opex/yr	2.2	3.5	6.6	10.5	M$/yr
Electricity cost	0.2	0.4	0.9	1.9	M$/yr
Costs	111.2	90.4	69.1	55.1	\$/t$_{dm}$
Costs	5.11	4.15	3.18	2.56	$/GJ

6.2. Economic performance

Based on the compact moving bed reactor, this study has estimated the investment costs for integrated torrefaction systems to be about 2.1–3.8 MUS$/t/h operational capacity. Investment figures for other reactor technologies and facilities ranged from 1.3 to 5.1 MUS$/t.h capacity. Shah et al. [66] give very low investment costs of 0.1–0.3 MUS$/t.h assuming an economic life of 30 years for the plant, although it is not clear which reactor technology is used. It is difficult to compare these investment figures as it is often unclear which investment elements are included to enable a bottom-up comparison. According to Ereev and Patel [116], the main source of inaccuracy in economic estimates is missing an investment component (e.g. indirect costs elements and contingency) rather than under/over-estimation. In this study, we increased the contingency to 30% to reflect technological uncertainty, whereas typical contingency values for energy projects of proven technology are between 10 and 25%. For specific projects, one would need to account for country specific costs such as correcting construction costs for country specific labour cost, environmental protection costs and equipment delivery costs (typically 10% of the purchased equipment cost). The factorial approach employed in this study is practical for new technologies and estimated production costs are theoretically accurate within ±30%.

Production costs of TOPs were estimated to be between 3.3 and 4.8 US\$/GJ$_{LHV}$ for operational scales of between 50 and 250 kt/yr, with an uncertainty of ±38–48%. This was only done for woody biomass.[19] It is technically feasible to scale up to 500 kt and reduce costs to 2.6 US\$/GJ$_{LHV}$. However, economically feasible torrefaction plants are currently in the range of 200–250 kt/yr, based on multiple torrefaction reactors, mainly due to feedstock supply limitations. In the future 500 kt/yr plants may be achievable. For comparison, van der Burg [94] gives the processing cost of landed TOPs at 2.28 $/GJ while Shah et al. [66] gives production costs of about 0.8 US\$/GJ$_{LHV}$.

With expected technological learning, TOPs production costs are expected to fall to within an average range of 2.6–5.1 US\$/GJ$_{LHV}$ with an uncertainty margin of ±20–24% (based on variation in Capex ranges). If pre-learning uncertainties are not taken into account, the production costs decrease by about 20% and average costs are estimated to be from 2.1 to 4.1 $/GJ. However, these uncertainties are real as current experience with first pre-commercial plants indicate that initial investment cost were underestimated and companies are investing more capital into fine-tuning and reconfiguring their facilities to achieve desired product characteristics. Estimating the cost reductions was based on future cumulative system installations up to 2030 based on Sikkema et al. [135]. However, depending on the attractiveness of torrefaction, it is anticipated that all traditional wood pellet facilities would be converted into integrated torrefaction plants to take advantage of this technology [20]. We chose a conservative learning rate of 2% since most components are mature and learning is mainly in their integration. Our estimates (total installed capacity of 28 Mtonnes by 2030) are also conservative considering that Vattenfall alone has target to co-fire 10 Mtonnes of biomass by 2020 [141]. Another approach could have been to estimate future global energy scenarios e.g. based on the IEA Blue Map scenario [142], which targets a 50% CO_2 reduction by 2050. To meet the desired targets, installed capacity of power from biomass must increase by 10 GW each year until 2050 or over 10 Mtonnes capacity must be added each year leading to significantly higher capacity doublings[20]. It is important to note that technological learning is expected to occur around the torrefaction reactor, and not primarily within the reactor – reactors are mature technologies in their own right. Important optimisation is expected to occur around integration of the torgas loop, combustor, heat exchangers as well as nitrogen feed.

6.3. Technical performance

The performance of the torrefaction process is mainly based on its ability to achieve efficient and uniform heat transfer to the biomass, optimised torgas use for operation below autothermal conditions, precise adaptability to feedstock characteristics (especially moisture content) and final product requirements (such as heating value and energy density). Its mass and energy yield are important indicators of the performance of the torrefaction process and depended strongly on the moisture content and heating value.

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[19] For straw, one would deduct the costs of pre-drying step, but this is rather simplistic as the heat integration of various components for a purely straw system would require a different setup compared to a woody biomass system. Ideally, an integrated torrefaction facility should be able to accept feedstocks with different characteristics and optimally adapt its processes.

[20] But such linear increase also seems unlikely, typically technology growth follows an S-shaped pattern, so smaller increases in initial years are plausible.

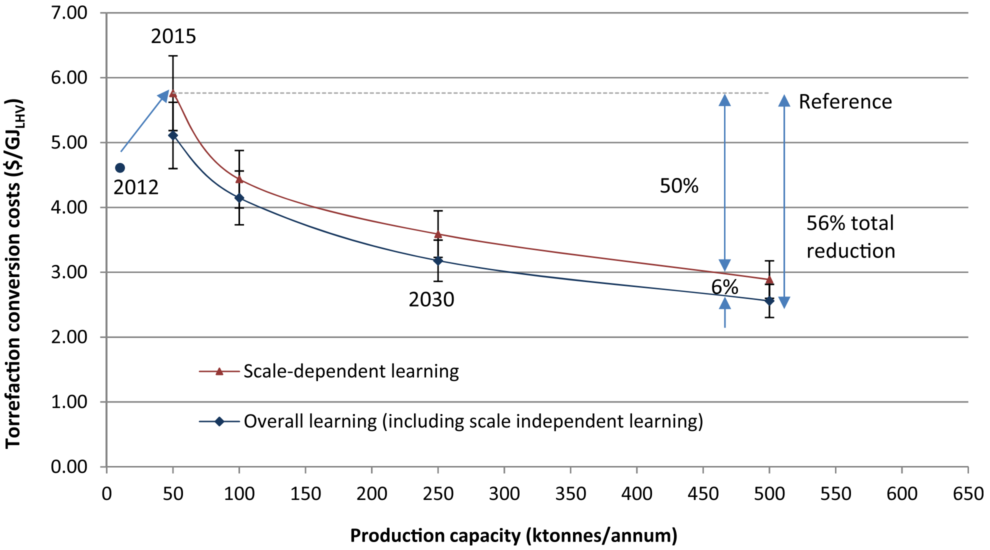

Fig. 8. Estimated future torrefied pellet production costs in 2030 (based on woody biomass, price of feedstock is not included).

This study has presented simplified mass and energy balances of the torrefaction process, which are more detailed than the theoretical balances in previous studies (e.g. Refs. [21,24]). Feedstock to product ratio for woody biomass was estimated to be 2.10–2.48 and the thermal efficiency of the process was 93–94%, and depending on the moisture content (40% and 45% respectively) and on the calorific value of the biomass feedstock (16.4 and 18.1 GJ$_{LHV}$/t$_{dm}$ respectively). Based on woody biomass with 18.1 GJ$_{LHV}$/t$_{dm}$, simulated feedstock to product ratios range from 1.6 to 3.6 and efficiencies range from 86% to 97% for corresponding moisture content of 60–20%. Theoretically, the feedstock to product ratio range from 1.35 to 3.6 and efficiencies range from 94 to 98%. More detailed data cannot be presented as the information is confidential. However, key parameters presented in these balances were estimated by verifying them with practical figures from a pilot plant. Besides, the model itself is built and based on knowledge from an existing torrefaction plant. To simplify the modelling, and ensure confidentially, internal energy streams such as flue gases and torgas show higher energy content than their actual energy content. This was mainly the result of assigning the energy conversion losses (in drying, torrefaction, combustion and heat exchange) within the process to the energy content of the gases.

Overall, the presented mass and energy balances are simplified compared to the actual balances, but do represent the current situation very well, especially regarding the main outcomes in the form of thermal efficiency and feedstock to product ratio. The presented mass and energy balance for the torrefaction of straw is based on theoretical assumptions since torrefaction of straw does not yet occur, which result in higher uncertainties regarding the mass and energy streams. Torrefaction of straw can achieve a smaller feedstock to product ratio of 1.55 and a higher thermal efficiency of 96%, due to the omitting of the pre-drying step in the process – assuming moisture content of 20% and heating value of 15 GJ/t$_{dm}$. Variation of moisture content from 10 to 25% results in feedstock to product ratios of 1.37–1.65 and efficiencies of 95.7–97% respectively. The projected performance remains uncertain given that other characteristics of straw such as lower bulk density and higher sulphur and chlorine content do require changes in the process design. In contract, Svoboda et al. [56] give lower mass and energy yields for torrefaction of grass and wheat straw compared to woody biomass. However, Carter [47] also experimentally show promising results for using switchgrass; Chen et al. [53] using coffee residues and rice husks; Patel et al. [59] using cotton stalk and bagasse and Medic et al. [44] using corn stover.

Furthermore, the degree of hydrophobicity and grindability of torrefied biomass is uncertain, and these are important characteristics for handling and use when comparison is made with coal. It is also not fully clear if the torrefaction process can efficiently accept a wider variety of biomass feedstocks such as agricultural residues. In addition, it is still not clear if torrefied pellets require additional binding materials and how these affect fuel characteristics. Also, no commercial scale tests have been conducted for torrefied material to verify demonstration level results.

7. Summary and conclusions

This study has shown that with current technology and based on modelled conditions with the compact moving bed reactor, woody biomass can be torrefied with an thermal efficiency of 94% (in the range 70–97%) and with a mass efficiency of 48% (in the range 28–77%) on a dry ash free basis. For straw corresponding energetic efficiencies are 96% (in range 95–97%) and mass efficiency of 65% (range 61–73%). In the long term the technical performance of torrefaction processes is expected to improve, especially the thermal efficiency. For woody biomass, energy efficiencies are expected to be at least 97% as optimal torgas use and efficient heat transfer are realised. Similarly, future energy efficiencies for straw processing are expected to be at least 98%. Of importance to torrefaction system performance is the achievement of consistent and uniform product, at desired end-use heating value and energy density. Also, it is expected future production processes would identify suitable process conditions that would produce the ideal TOP in terms of grinding energy, hydrophobicity, densification energy requirements, pellet robustness and energy density.

Short term investment costs for integrated compact moving bed reactor base torrefaction systems are estimated to be between 2.1 and 3.8 MUS$/t.h for systems with maximum capacity of 250 kt/yr. Corresponding production costs for woody biomass TOPs were estimated to be between 3.3 and 4.8 US$/GJ$_{LHV}$. The study has shown that significant reductions in TOPs production costs of over 50% of current production cost estimates are possible in long term due to scaling up and technological learning. Future TOPs production costs are expected to fall to within an average range of 2.1–4.1 US$/GJ$_{LHV}$ for woody biomass, but expected increases in pre-learning costs are likely to drive production costs upwards to an average range of 2.6–5.1 \$/GJ. At such cost levels, torrefied pellets would become competitive with traditional pellets.

Torrefaction is a promising biomass energy pre-treatment technology, with potential to make a major contribution to the commodification of biomass as a renewable energy resource. Given their ability to directly replace coal, torrefied pellets have huge market potential. However, there are still many challenges such as bringing production costs down while producing a homogeneous, fully hydrophobic and stable product, capable of fuel flexibility. Of key importance is efficient heat integration and optimal use of torgas to achieve autothermal operation with minimal safety risks.

Depending on the feedstock supply costs, production of torrefied pellets will improve the economics of long distance shipment of biomass from various production of the world to centres of high biomass demand. For full commercialisation, torrefaction reactors still require to be optimised to economically meet end use requirements and achieve market standardisation of the product. Rapid deployment and technological learning would be key to bring production costs down and making the torrefied pellets competitive. Ultimately, the presented advantages of torrefied pellets need to be proven or scaled up in order to meet commercial expectations.

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